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13. ABSTRACT (Maximum 200 words)
Shock tube studies of shock enhanced mixing of helium into air were reported utilizing the Rayleigh scattering technique. Because of their greater sensitivity in the low concentration range, these measurements were believed to be more accurate than those obtained with laser induced fluorescence. The results indicated that mixing was more rapid and more complete than reported previously. Preliminary work on the consequence of multiple shocks has been promising. Work began on the interaction of shock induced mixing with shear layers in the GALCIT M = 2.5 supersonic wind tunnel. Experiments concerning the details of combustion in large vortices in the Caltech Unsteady Combustion Facility progressed very well using simultaneous measurements of pressure, shadowgraphy, and chemiluminescence. These results reveal a very different ignition mechanism and combustion pattern than had been anticipated.

14. SUBJECT TERMS
Supersonic Combustion, Vortex Combustion, Shear Layers, Vorticity Generation, Hypervelocity Mixing, Shock Enhanced Mixing

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1. RESEARCH OBJECTIVES

This report describes the first year of Grant AFOSR-90-0188 which is essentially a continuation of three year University Research Initiative Contract F49620-86-c-0113. This latter investigation aimed to demonstrate the high degree of mixing enhancement between hydrogen and air that could be induced through the appropriate interaction of relatively weak shock waves with the interface between the two gases. This interaction generated strong streamwise vorticity at the interface which, in turn, led to a rapid distortion of the interface and correspondingly rapid mixing between the hydrogen and air. The experimental and computational investigations were sufficiently successful that an injector mixer suitable for a scramjet was designed. With NASA support, models were built and tested in a Mach 6 wind tunnel at Langley Research Center with very satisfactory results. An invention disclosure was made and the patent claim is being pursued by the U.S. Air Force.

There were, however, several aspects of the shock enhancement that were not understood. The two most important of these were the later stages of mixing and the scaling of the process with both size and shock Mach number. In addition, we saw the possibility of utilizing the shock interaction mechanism to control the distribution of heat release along the direction of flow. These items formed the basis of the grant which is the subject of this report.

Shock Tube Experiments. - Because of the very accurate correspondence of the time-dependent development of the two-dimensional vortex structures with the streamwise development of the three-dimensional field, shock tube experiments have proven exceedingly useful. Under the present grant, experiments in the GALCIT 17-inch Shock Tube are being employed to examine the scaling of the mixing process with shock Mach number and the influence of multiple shock impingement. These are being carried out using vastly improved optical techniques.

Combustion in Large Vortices. - The shock tube experiments have concentrated upon the mixing mechanism, while the combustion process itself has been investigated using our Unsteady Combustion Facility. Vortices which may grow to diameters the order of 3 inches are formed by operating the facility in a resonant pulsed mode. Because of its relatively large size, the progress of the combustion process is followed by optical methods in considerable detail. The vortex combustion details may be followed for times exceeding 6 milliseconds, which is more than adequate for our purpose.

Computational Study of Shock Enhancement. - The experimental research is both expensive and time consuming, and, as a consequence, we must assure that each of the experimental points addresses a well-defined issue. From the beginning of this project we have made extensive use of computations to explore conditions that merit experimental effort. Fortunately most features of the interfacial instability and the rolling-up process can be modelled with an inviscid code, an economy of both time and expense which has allowed a wide and revealing examination of shock interface interactions. The results have proven successful,

not only to pinpoint valuable experimental conditions but also as a considerable aid in studies of Mach number and geometric scaling.

Interactions with a Shear Layer. – The interactions of shock waves with a strong density discontinuity, which is the main focus of this project, seldom occurs in the absence of shear layers. The vorticity generated by the shock interaction is almost entirely aligned with the direction of free stream flow, while the shear flow generated, for example, by the presence of a combustion chamber wall lies largely normal to the stream direction. The complex mutual interaction of these two vorticity fields is the subject of experiments in the small GALCIT supersonic wind tunnel. Although the tunnel Mach number of 2.5 and the size of the working section are lower than one would wish, it does give a very convenient opportunity to explore the interaction between the shock-enhanced mixing of a helium jet in air and a thickened wall boundary layer of the wind tunnel.

2. STATUS OF RESEARCH

Investigations in the GALCIT 17-inch Shock Tube

The experiments in the shock tube to measure the mixing rate of helium into air correspond to the hydrogen jet mixing problem through the relation of time in the two-dimensional time-dependent problem to the streamwise distance in the steady mixing problem, as explained in Marble et al.(1986a). The configuration of the experiment in the shock tube, Figure 1, shows the intersection of the laser sheet with the helium jet and the resulting "print" of the distorted helium jet after the passage of the shock has moved the jet fluid downstream of its original position. The details of the data acquisition and

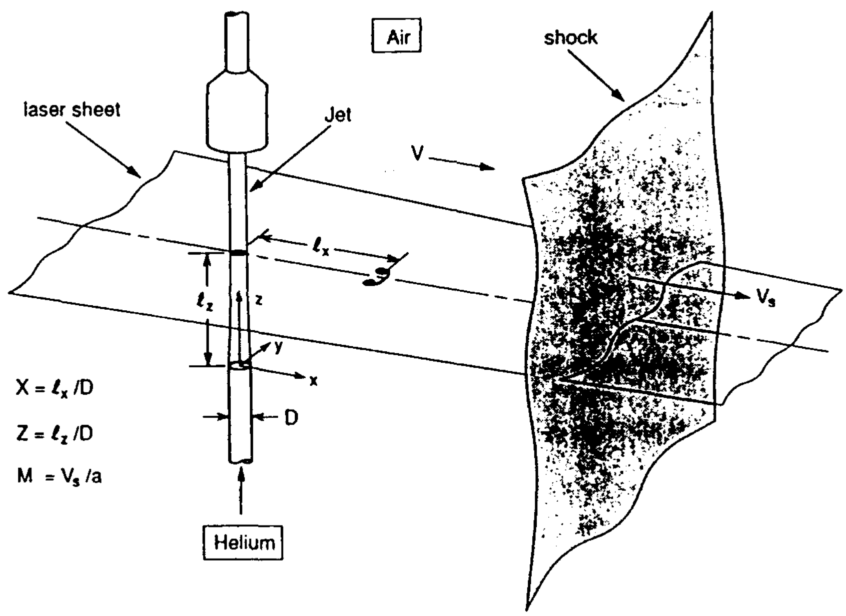


Figure 1. Helium Jet/PLIF Configuration

helium density evaluation methods are discussed in detail in Jacobs (1990), and these results provide a measure of the rate of mixing. These data show a core region in which the helium concentration is quite close to its original value. As a consequence, the area of this region is a convenient measure of the amount of unmixed helium. A plot of this area versus time then gives a good idea of the shock enhanced mixing rate. These rates depend upon the shock Mach number and the original size of the helium jet. Jacobs (1990) was able to adapt the analysis of Marble (1985) to provide a modified time scale which gives a reasonably unified presentation of the measurements. Such a plot is shown in Figure 2, taken from Jacobs (1990).

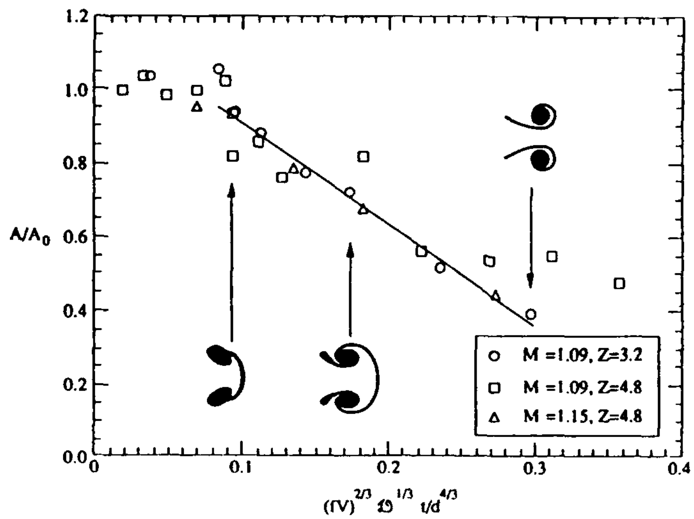


Figure 2. Mixed Cross Sectional Area Ratio Versus Scaled Time. (A listing of notation, including that for the above figure, appears on page 12.)

Although the shock tube investigations utilizing laser-induced fluorescence of biacetyl have been extremely important in our exploration of the mechanism of shock enhanced mixing, Marble et al. (1990), Jacobs (1990), Jacobs (1991), certain inherent features of the technique limit refinement of helium density distribution measurements. The biacetyl was intended as a marker for the helium and, as such, was mixed in very small concentrations with the helium before firing the tube. The features that concerned us so far as accuracy was concerned were the different diffusion rates of helium and biacetyl and the very nonlinear sensitivity of the camera at low intensity levels.

To address this issue steps were taken to implement the Rayleigh scattering technique. The advantages of this method are i) no diluent (biacetyl) is involved, rather the molecules of interest are followed, and ii) the response with a new camera is linear down to the concentration range where "noise" dominates. The main drawback is the weaker signal resulting from the Rayleigh scattering. Although we had anticipated from the beginning the possibility of employing Rayleigh scattering, significant modification to our optical setup was required. The power of the laser was increased by more than a factor of ten by using a different dye, a new camera with linear response was acquired, and an extensive calibration of each camera pixel was required. Two views of the modified shock tube setup are shown in Figure 3 and Figure 4.

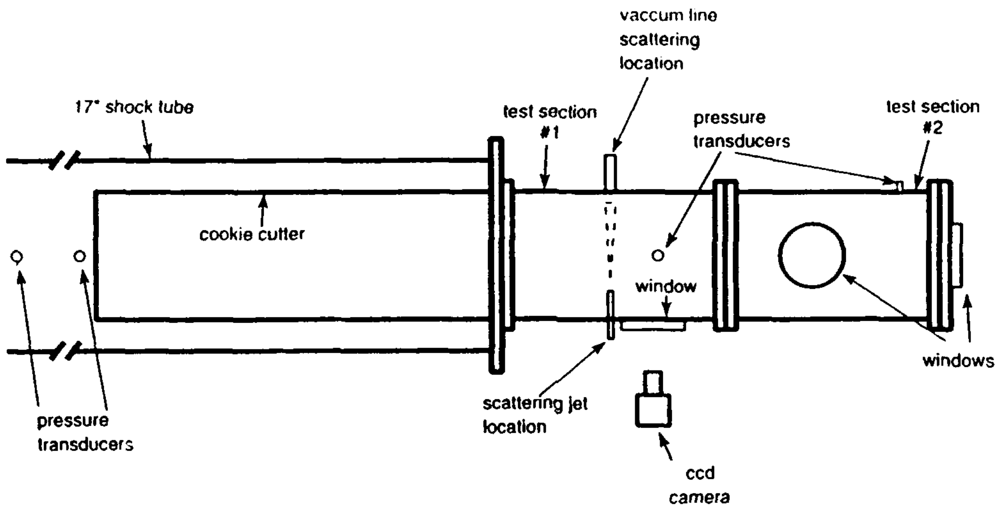


Figure 3. Side View of Shock Tube Mixing Experiment.

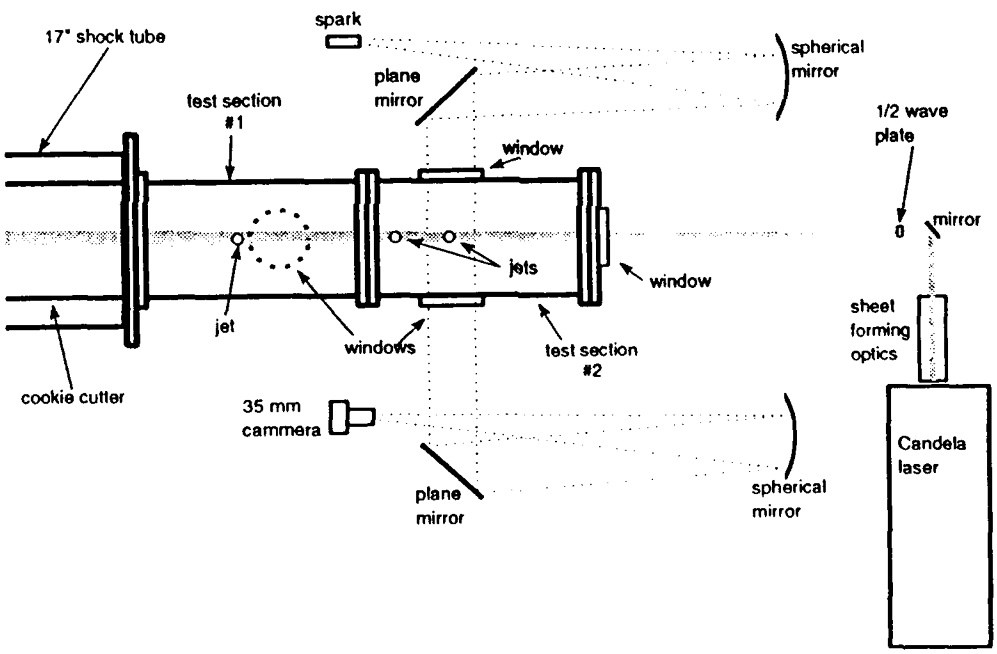


Figure 4. Top View of Shock Tube Mixing Experiment

Results that we have obtained using the Rayleigh scattering technique have revealed new aspects of the shock-induced mixing process that were not available from our earlier work. First, the differential diffusion between the biacetyl and helium introduced errors, of which we were aware, of significant magnitude. Second, the sensitivity of the the old camera to laser induced fluorescence at low concentrations was sufficiently limited that a mass balance of helium could not be made and the degree of mixing was consistently underestimated. The accuracy of our present method has proven sufficient to eliminate these difficulties. The current Rayleigh scattering sensitivity allows determination of helium mole

fraction to within 4%, and, in the far field, this noise level may be effectively cancelled to the extent that helium mass conservation is experimentally satisfied to a very high degree. This new data, which is now being acquired, reveals degrees of mixing much higher than we had reported earlier. This is a consequence of our former inability to follow the very low helium concentrations corresponding to the thoroughly mixed material.

Figures 5a and 5b show examples of the Rayleigh scattering results for two time intervals after shock passage, both for the same shock Mach number of 1.073. (Unfortunately, the reproduction of the copier does not do justice to the quality of the results!).

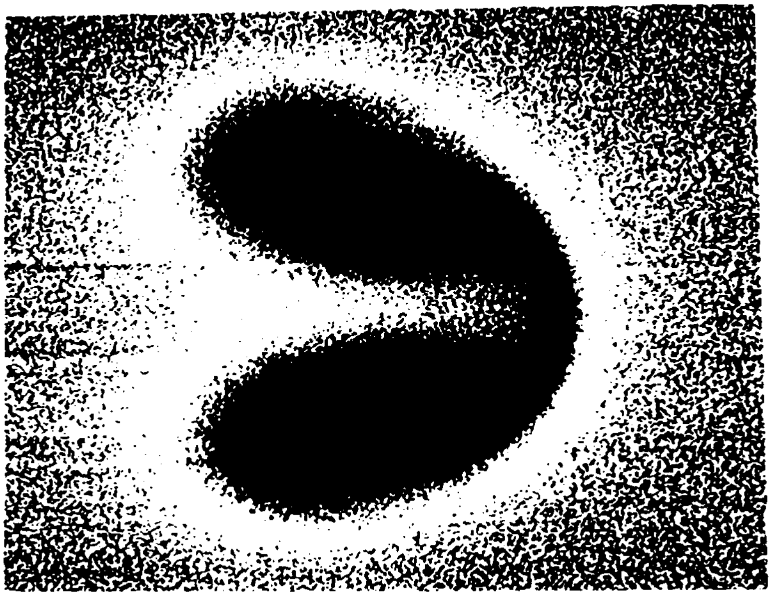


Figure 5a. Helium Density Distribution, M = 1.073, Early Time.

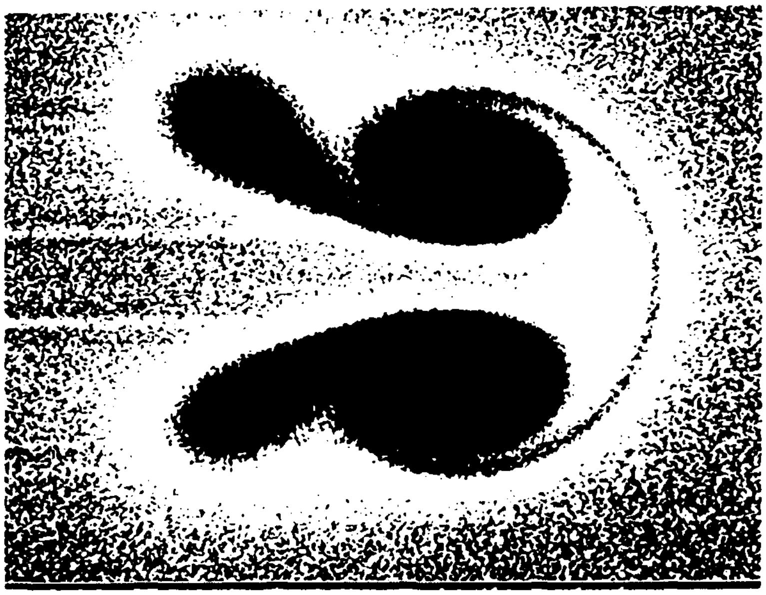


Figure 5b. Helium Density Distribution, M = 1.073, Later Time.

Investigation of Combustion in Large Vortices

The large vortices for this part of the investigation were generated in the Caltech Unsteady Combustion Facility by exciting one of its oscillatory modes to a relatively high amplitude. A sketch of this facility set up for the current experiment is shown in Figure 6. When operating in the pulsing mode, large

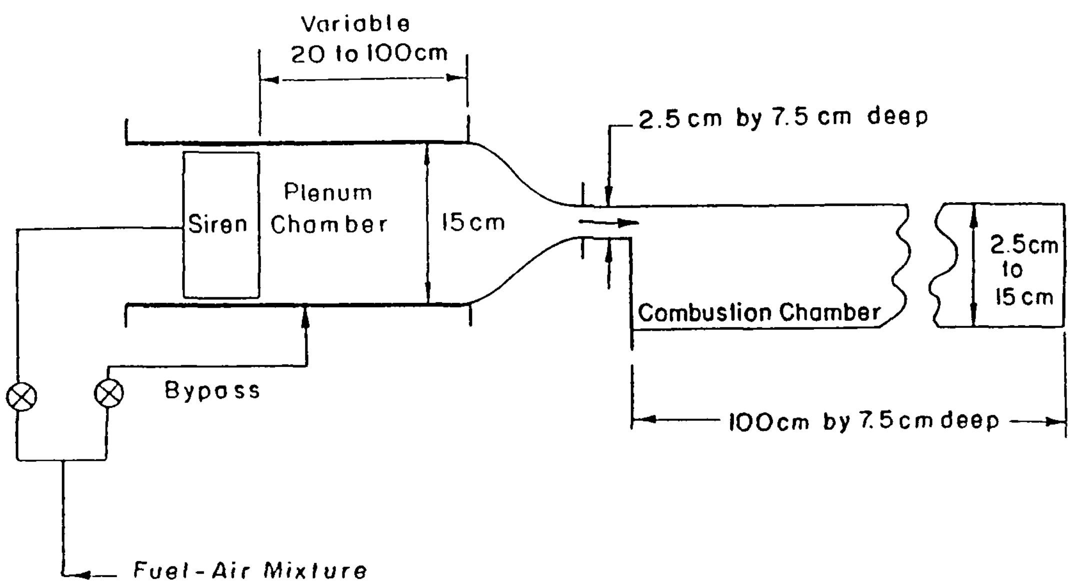


Figure 6. Unsteady Combustion Facility.

vortices are formed at the downstream facing step at the inlet to the combustion chamber, Sterling & Zukoski (1987). The ignition, combustion, and eventual consumption of the mixture in these vortices may be observed through transparent walls of the combustion chamber. In the configuration shown, vortices were produced at the rate of 231 per second. Time-resolved radiation intensity measurements were made through use of a GE TN2505A solid state charge injection device (CID) camera which divides the field of view into a grid of 360 by 240 pixels. The light intensity measurements allow for the quantitative estimation of the heat release rate, since it is generally accepted that the local chemiluminescence is proportional to the mass rate of chemical reaction at the point under consideration. Flow visualization is accomplished with a standard Z-configuration optical arrangement for shadowgraphy and high-speed cinamatography. Use of the CID camera in conjunction with spark shadowgraphy allows examination of the progress of combustion through the vortex structure. At a desired phase of the cycle, a spark shadowgraph is taken of the vortex. Fifteen microseconds later, an image of the chemiluminescence is obtained with the CID camera. The exposure of this picture is 60 microseconds.

For the high-speed motion pictures, taken with the Hycam camera, pressure transducer and hot wire measurements were used in conjunction with a photomultiplier tube. The photomultiplier tube, which gathers emitted radiation, was substituted for the CID as the Hycam setup, Figure 7, did not permit its use.

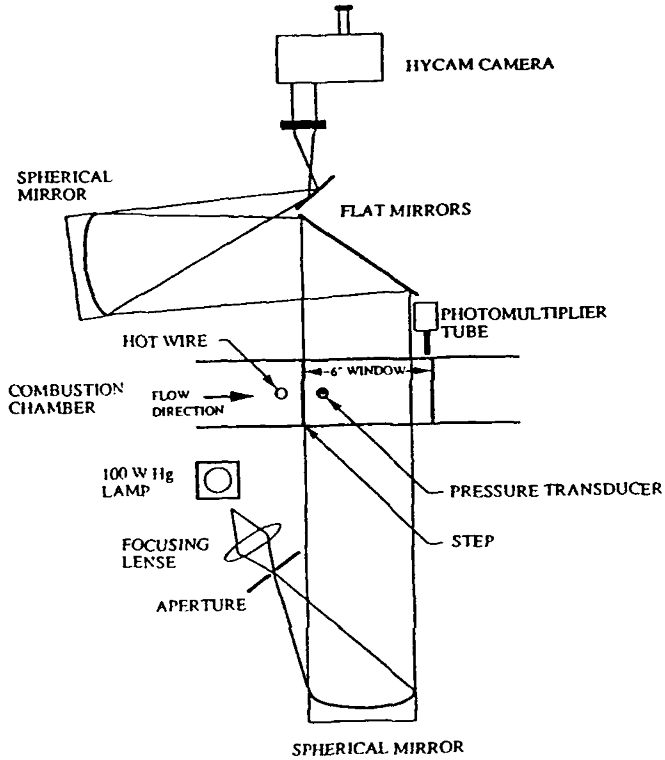
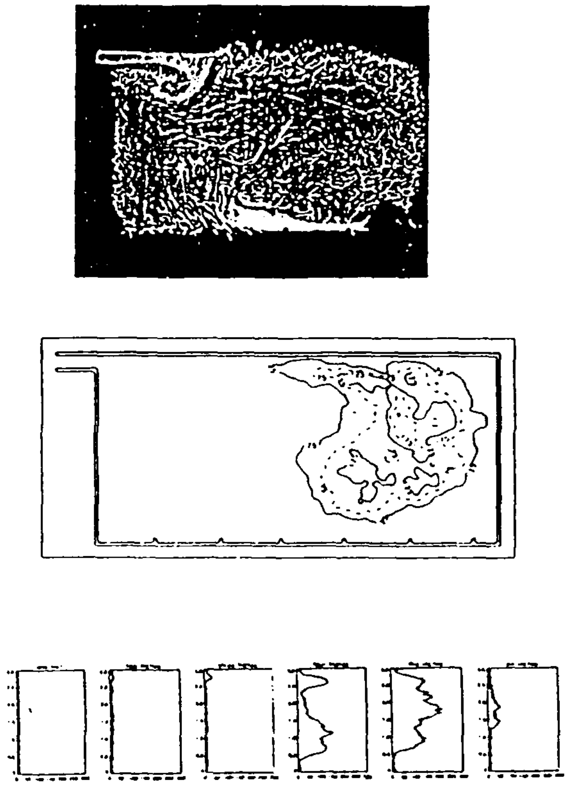


Figure 7. Hycam Camera Setup.

Typical results for the 3-inch combustion chamber configuration, Figure 6, are shown in Figures 8 and 9, which contain images of vortices shed at three different times. Figure 8a shows a vortex centered 1.5 inches from the step and another centered 5 inches downstream. The two structures have been in the duct for 2.4 msec and 6.48 msec, respectively, measured from the minimum of the hot wire signal. *As is evident from the contour plot of the chemiluminescence*, Figure 8b, and from vertical intensity profiles, Figure 8c, at different locations, a negligible amount of light is being emitted from the vortex shed most recently. In contrast, the more fully structure exhibits a much stronger signal, indicating a much larger heat release rate per unit volume.

Figure 9a shows a vortex whose development lies between the two discussed previously. It was shed 4.08 msec before the photograph and is centered at 2.5 inches. A small region of combustion is evident in the core of the vortex, shown in the contour plot of Figure 9b. However, the more intense activity occurs on the outer surface near the top wall, where the tail of the previous vortex is acting as an ignition source. These results suggest that a very low level of combustion occurs near the lip of the step.

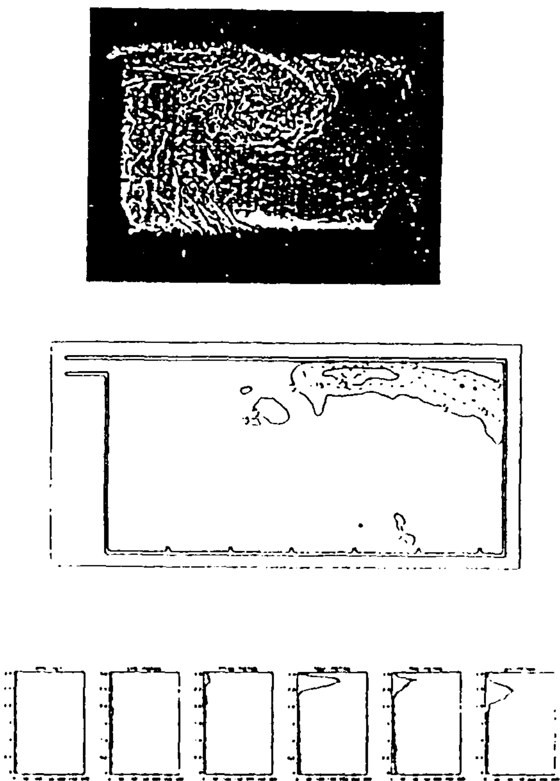


(a)

(b)

(c)

Figure 8. Vortices Shed at 2.40 and 6.48 Seconds



(a)

(b)

(c)

Figure 9. Vortex Shed at 4.08 Seconds

A sequence of intensified camera shots illustrating the progression of combustion through the vortex structure is given in Figure 10, for which the exposure time is now 26 microseconds. As the well-developed structure furthest from the dump plane begins to burn out, the vortex nearest the step begins to ignite, primarily at its upper leading edge. This burning gas is swept around the vortex until finally the entire structure is burning.

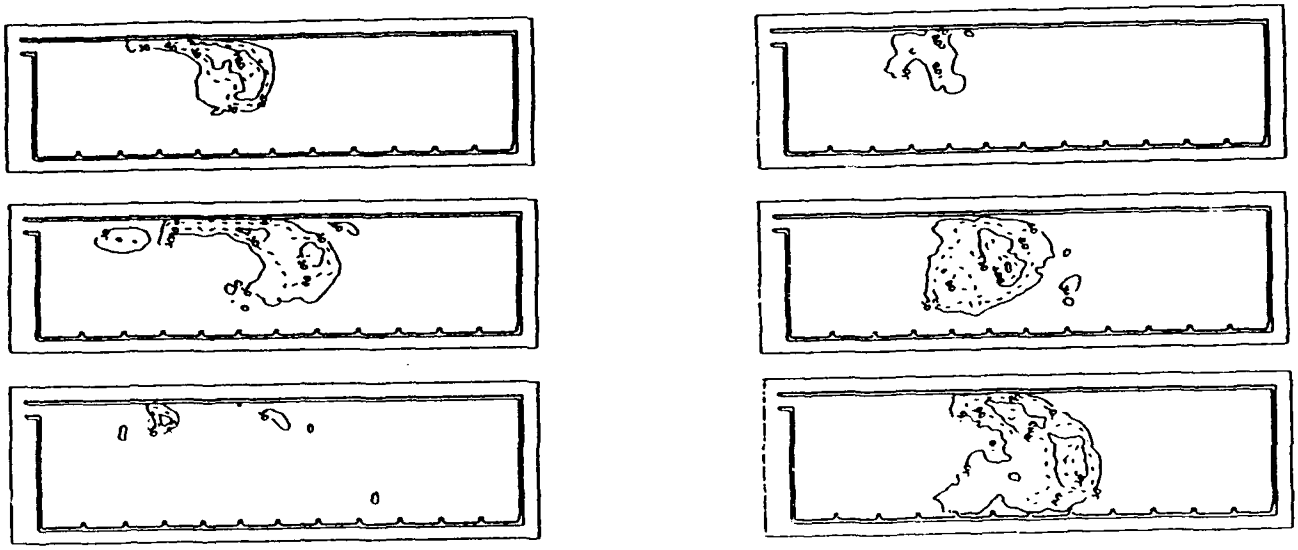


Figure 10. Progress of Combustion in the 3 inch Chamber

The radiation intensity measurements using the CID camera provide spatial resolution of flame chemiluminescence that has not previously been obtained for the pulse combustor flow fields produced in the Caltech Unsteady Combustion Facility. The results show a surprisingly small amount of heat release at the reactant product interface for early times in the vortex structure development. Thus the spark shadowgraphs taken "simultaneously" reveal sharp interfaces although very little combustion is present. However, as the vortex grows, mixing with the products of combustion degrades the sharp appearance of the shadowgraph, but the radiation intensity increases significantly. The absence of combustion near the burner inlet may be explained either by the thermal boundary on the step or by the high strain rates within the flame sheet during the early stages of the cycle.

Computational Studies

During our early studies of shock enhanced mixing of hydrogen in air, Marble et al. (1987a, 1987b) and later, Marble et al. (1990), it became evident that Euler code calculations gave a very good representation of the details that we were able to observe from shadowgraph photographs. The dominant reason for this success was that, in the very short times involved, the diffusion layers at the hydrogen-air interface grew a very small distance in comparison with the vorticity distortion scale of the interface. Earlier, Hendricks (1986) took advantage of this simplification in his studies, using a code developed originally by J. P. Boris of the U. S. Naval Research Laboratory. The code was obtained

by us through the courtesy of Dr. Eric Baum of TRW, who had made additions to it for use in shock tube studies. Over a period of three years, Hendricks performed extensive computational studies for both the shock tube experiment and the pulsed vortex generation that were instrumental in establishing conditions for the more time-consuming experiments that have been carried out. As the experimental results were obtained, sufficient confidence in the computations was developed that we were able to utilize them for extending the physical understanding of shock-induced mixing to different shock Mach numbers and different geometric configurations.

These studies were considerably expanded, together with further enhancements of the code, by Yang (1991). His results have provided additional insight into scaling laws for the process which should be relevant in technological applications of the shock enhancement principle. These studies are reported in Yang et al. (1991a, 1991b).

Studies in the GALCIT Supersonic Wind Tunnel

One of the important features that becomes evident when attempting to make technological application of the shock enhanced mixing, is the interaction of the streamwise vorticity induced by shock enhancement with the boundary layer vorticity which is predominantly normal to the flow direction. In the studies of the hypersonic injector carried out at NASA Langley Research Center, Marble et al. (1990), Waitz et al. (1991), Waitz (1991), this interaction proved to be important in choosing the physical configuration.

To examine this issue in detail, a cylindrical jet injector has been installed in the GALCIT Mach 2.5 supersonic wind tunnel. A sketch of the installation is shown in Figure 11. The test section, which is 5 cm high and 6.47 cm wide,

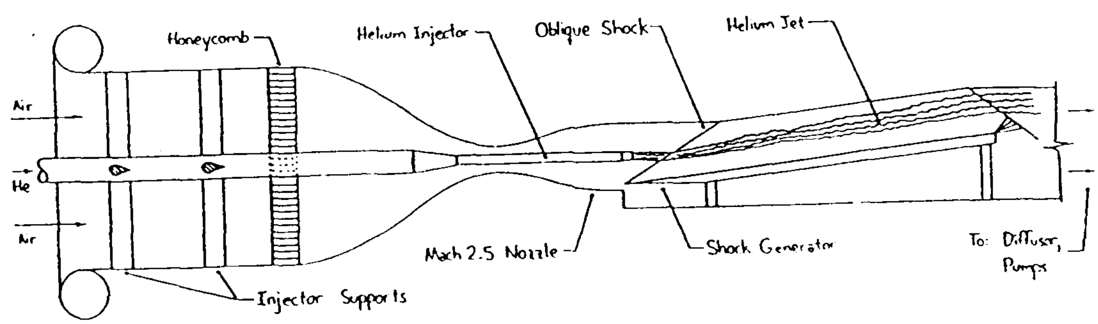


Figure 11. Shock Enhanced Mixing Experiment in GALCIT M = 2.5 Tunnel

has been modified to accommodate a cylindrical helium injector which discharges in the streamwise direction through a shock generated by a sharp edged plate. The angle of this plate may be adjusted to turn the air through an angle of up to 10 degrees. The tunnel modifications and the experimental installation have been designed and are under construction at present. It should be noted that the cylindrical helium injector enters the working section from upstream through

the settling chamber in order to avoid the interference that would be caused by entering through the tunnel wall. Measurements will be made using a light sheet scattered from ice particles formed by condensation and freezing of water vapor in the air.

Notation for Figures of Section 2.

a	Acoustic velocity in working section
A_0	Initial area of helium jet
A	Area of unmixed helium at time t
D	Diameter of helium injector
d	Diameter if helium jet at plane of laser sheet
$\mathcal{D}$	Diffusion coefficient of helium in air
fV	Forward velocity of vortex pair
ℓ_x	Distance of image downstream of helium jet
ℓ_z	Distance of laser sheet above jet discharge
M	Shock Mach number, V_s/a
t	Time after shock passage
V	Gas velocity following shock
V_s	Shock velocity

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4. PERSONNEL

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5. INTERACTION WITH INDUSTRY AND GOVERNMENT LABS

Professor Kubota has been in close contact with the high speed aerodynamics group at NASA Langley Research Center because of our experiments being carried out there in the Mach 6 High Pressure wind tunnel.

We have benefited greatly from the appointment of Professor J.L. Kerrebrock of MIT as a Sherman Fairchild Distinguished Fellow at Caltech. His close association with the NASP program allowed him to play an active role in our mixing research program and to contribute to our SCRamjet performance code about which more will be said subsequently.

Professor Marble serves as a member of the Committee on Hypersonic Technology for Military Applications of the Air Force Studies Board, the Hypervelocity Mixing Advisory Group, NASA Langley Research Center, the NASA Committee for Generic Hypersonics Program, and the Peer Review Group for Turbomachinery, NASA Lewis. He has recently been appointed Chairman of the Propulsion Panel, Aeronautical Technologies Committee of the Aeronautics and Space Engineering Board. Professor Marble has periodically given briefings to Pratt & Whitney and to Rocketdyne concerning the shock enhanced mixing study.

Professor Sedat Serdengecti of Harvey Mudd College, Claremont Colleges, spent the summer months at Caltech as Senior Research Associate and, during this period, undertook the development of a very general and flexible code for SCRamjet performance. This code allowed a most penetrating analysis of the consequences of mixing completeness and mixing rate on performance and cooling load for the SCRamjet.

As a result of the completion of the GALCIT Piston Shock Tunnel, Professor Zukoski has maintained close contact with Rocketdyne, who is the heaviest user of the tunnel. Dr. Zukoski has been instrumental in arranging future experiments of shock enhanced mixing on the Rocketdyne SCRamjet model at real conditions corresponding to a Mach number of 12. This will be the closest we have been able to come to having the AFOSR research applied to NASP hardware. Dr. Zukoski has continued to stay in close contact with the SCRamjet research group at NASA Langley Research Center.